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VALIDATION OF SIMULATED ATMOSPHERIC FIELDS FOR AIR QUALITY MODELING PURPOSES IN ITALY

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Abstract: The MINNI project supports policy makers in the elaboration and assessment of air pollution policies in Italy. In MINNI, an Eulerian Atmospheric Modelling System (AMS), built around the chemical transport model FARM (Flexible Atmospheric Regional Model), has been applied to several reference years. The meteorological fields necessary to drive air quality simulations at 4x4 km^2 space resolution have been reconstructed for years 1999 and 2005 by means of the diagnostic meteorological model LAPS (Local Analysis and Prediction System) employing data assimilation techniques. The first guess background meteorology has been provided by an annual simulation of the prognostic non-hydrostatic meteorological model RAMS (Regional Atmospheric Modelling System) with space resolution of 20x20 km^2 and time resolution of one hour.

Model results for year 2005 have been compared with independent observations collected by the Friuli Venezia Giulia Region meteorological network, in order to identify strengths and shortcomings of the meteorological fields. The comparison of LAPS results with RAMS fields and observations shows a satisfactory description for all the considered meteorological variables over coastal and inland plains, which are the main target areas for air quality assessment and management. The model performance deteriorates over mountain areas, where model resolution is insufficient to properly resolve Alpine valleys feature and no observations are available to feed LAPS assimilation process.

Key words: *data assimilation**,** air pollution meteorology*

INTRODUCTION

Since 2002, on behalf of the Italian Ministry of the Environment, ENEA has been leading a national Project, named MINNI (National Integrated Modelling system for International Negotiation), for the development of an Integrated Assessment Modelling system to support policy makers in the elaboration and assessment of air pollution policies at international, national and local level. MINNI consists of two main components: a multi pollutant Eulerian Atmospheric Modelling System (AMS), and the RAINS-Italy Integrated Assessment Model. The atmospheric transfer matrices provide the link between the AMS and GAINS-Italy. The AMS includes emissions, meteorology and pollutants dispersion/chemistry modules. In its first version, AMS was applied to estimate pollutants deposition and air concentration fields over Italy, with a spatial resolution of 20x20 km^2 and an hourly time step over the whole 1999 year. An improved version of AMS with a spatial resolution of 4x4 km^2 has been later implemented and applied on both year 1999 and 2005 (Vitali *et al.*, 2008). A second phase of MINNI project is presently ongoing and foresees simulations for years 2003 and 2007. The meteorological data set is used to drive MINNI project air quality simulations, but it is also distributed to Regional Environmental Protection Agencies (ARPA) and other users to support downscaling activities and air quality simulations at local scale possibly employing different air quality model types and/or different emission data sets.

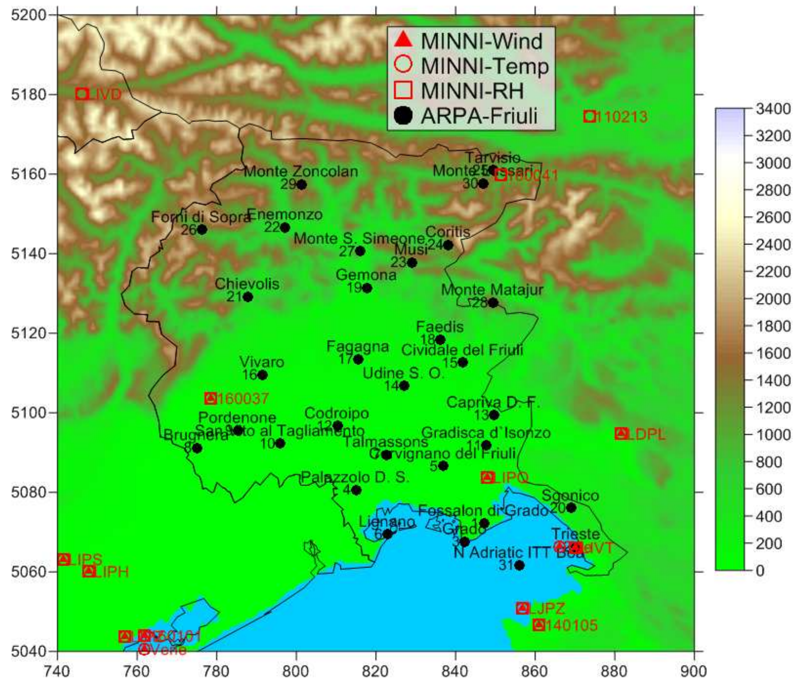

Figure 1. Geographic location of meteorological stations used to produce MINNI meteorological analyses (red symbols) and ARPA Friuli Venezia Giulia stations employed for model verification (black dots and numbers indicating station order used in Figures 3 and 6).

The 2005 simulation was carried out using LAPS (Local Analysis and Prediction System; McGinJey, 1989, McGinJey *et al.*, 1991), in order to improve spatial resolution by means of a diagnostic tool and measured data assimilation. LAPS "is a mesoscale meteorological data assimilation tool that employs a suite of observations (meteorological networks, radar, satellite, soundings, and aircraft) to generate a realistic, spatially distributed, time-evolving, three-dimensional representation of atmospheric features and processes" (Hiemstra *et al.*, 2006). LAPS has been initialized by the 20x20 km^2 spatial resolution fields calculated by the prognostic non-hydrostatic model RAMS (Regional Atmospheric Modeling System; Cotton *et al.*, 2003), and by surface observations. For air quality simulation, LAPS meteorological fields are used to drive the Flexible Air quality Regional Model (FARM, Silibello *et al.*, 2008; Gariazzo *et al.*, 2007).
To verify the meteorological fields reliability and possibly define the limitations of the dataset, model results for year 2005 have been compared with independent observations over the area of Friuli Venezia Giulia, an Italian region located at the North-Eastern bounds of Italy. Friuli has a complex topographical structure, with the Eastern Alps mountain range surrounding plains and the northernmost Adriatic Sea coast, in a quite small territory, therefore being of particular interest for meteorological models validation. Moreover, the regional meteorological network, managed by ARPA Friuli Venezia Giulia, provides a comprehensive cover of the different environments and landscapes (Figure 1). The comparison between model results from RAMS and LAPS and measured values was carried out using model evaluation statistical indexes and direct comparison of observed and modeled data.

METEOROLOGICAL MODELLING

Background National Scale Meteorological Fields

The meteorological fields at national scale have been reconstructed by means of the prognostic non-hydrostatic model RAMS Version 6.0 (Cotton *et al.*, 2003) using a 2 way nested grid system, with an outer grid covering a large part of central Europe and the Mediterranean Sea, with a resolution of 60x60 km^2, and an inner grid including the target area for the air quality simulations and having the same horizontal resolution of 20x20 km^2. Initial boundary conditions and data assimilation have been based on mesoscale analyses produced by means of the RAMS pre-processor ISAN (ISentropic ANalysis) with a time frequency of 1 hour. ISAN implements an optimal interpolation method based on Barnes algorithm. ECMWF analyses, available every 6 hours with a horizontal space resolution of 0.5 degrees, have been used as background fields. WMO surface observations, retrieved from ECMWF archives, were mostly available with time frequency of 1 and 3 hours over the whole of Italy. Nudging technique has been employed by RAMS to assimilate data analyses during the whole model simulation through an additional forcing term of the conservation equations for pressure, temperature, water vapour and momentum. Sea surface temperature has been defined on a daily basis from data included in ECMWF operational analyses. Every week RAMS simulations have been re-initialized on the basis of ECMWF analyses and surface observations. RAMS implements a multilayer soil model coupled to the atmospheric model to allow the evaluation of heat and moisture fluxes. To limit initialization influence, the initial soil status, on January 1st at 00 UTC, has been obtained from a preliminary model simulation extended to the whole December 2004. The subsequent simulations have been initialized from the 3D soil fields produced by previous week simulation allowing continuity of soil status during the whole yearly model run.

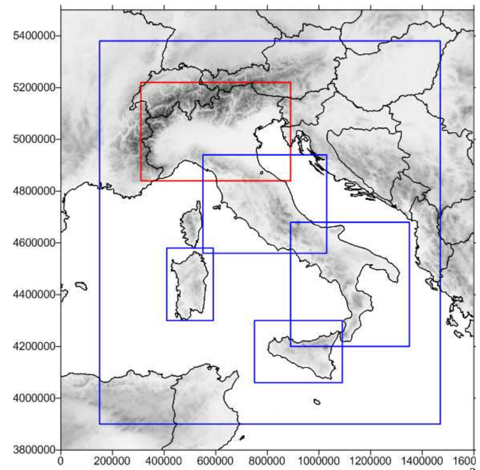

Figure 2. MINNI National domain (20x20 km^2 resolution) and Regional sub-domains (4x4 km^2 resolution).

Regional high resolution meteorological analyses

LAPS is an ensemble of modules that produce surface and three-dimensional analyses of wind, temperature, moisture and clouds merging a first guess meteorological field with observational data to generate a new atmospheric analysis. Depending on the dataset, different analysis methods such as Kalman filtering (McGinley, 2001), traditional Barnes (Barnes, 1964) and variational minimization techniques (Lewis, 1971), are used in the codes.
To realise an hourly representation of 2005 meteorological fields over the whole Italian peninsula, with a resolution of 4x4 km^2, the target domain has been subdivided into 5 sub-domains including respectively Sicily, Sardinia and Northern, Central, Southern Italy (Figure 2). Although one of the main characteristics of LAPS is the possibility to include a wide range of measurements, for its application within the MINNI project only surface meteorological measurements were used. This choice was due to the extremely inhomogeneous time and space distribution of other available data types over Italy, while a diagnostic model needs a temporal homogeneous dataset, in order to preserve temporal continuity of meteorological fields. The surface meteorological data used for LAPS analysis were extracted from the ECMWF database. All the stations showing a time frequency lower than 3 hours or frequent or long lasting data gaps were discarded. The resulting surface observations database was checked for outliers before applying a temporal linear fit in order to obtain a continuous hourly database of each station.

ANALYSIS

Methods for statistical evaluation

Several statistical indexes were calculated in order to perform the model evaluation: *Fractional Bias* (*FB*), *Root Mean Square Error* (*RMSE*), *Normalized mean square error of the Normalized Ratios* (*NNR*), *Mean square error of the Normalized Ratios*

(*NR)* (Poli A.A. and Cirillo M.C., 1993), *Index of Agreement* (*IOA*), *Correlation coefficient* (*R*) and *Coefficient of determination* (R^2). For the sake of brevity only results for *FB* and *IOA* (Equations 1) will be presented here; these two indexes were chosen because they summarize the main features of the comparison well.

$$FB = \frac{\overline{X}_O - \overline{X}_M}{0.5\,(\overline{X}_O + \overline{X}_M)}; \qquad IOA = 1 - \frac{n\,RMSE^2}{\sum_i \left(\left| X_{M_i} - \overline{X_O} \right| + \left| X_{O_i} - \overline{X_O} \right| \right)^2}; \qquad (1)$$

In equation 1 X_M and X_o represent model-estimated and observed data respectively, the subscript *i* refers to the i^{th} hour (all the hours of the year for which observed data were available have been used in our analysis) and overbar symbol refers to mean values over the whole data set.
Better matching corresponds to *FB* values closer to 0 and to *IOA* values closer to 1.

Statistical results
Comparison between model-estimated and observed data was made for common meteorological variables such as wind speed, temperature and relative humidity. Our goal was to examine any improvement in LAPS meteorological fields with respect to the first guess fields calculated by RAMS. In all the Figures presented LAPS data are shown in red and RAMS data in black. In Figure 3 *IOA* values, calculated from whole hourly data of the year, are shown for all the available stations, ordered by increasing height a.s.l.. The 31^{st} stations refers to a buoy data as evidenced in Figure 1.Values of *IOA* very close to 1 are obtained for stations sited at coastal and internal plain locations, in particular for temperature and humidity analysis. It is worth noting that LAPS humidity fields are largely improved with respect to RAMS ones at heights lower than 500 m a.s.l., while model performances deteriorate for all variables at higher altitudes for both RAMS and LAPS data. Moreover, LAPS analyses do not improve RAMS fields at mountain stations.

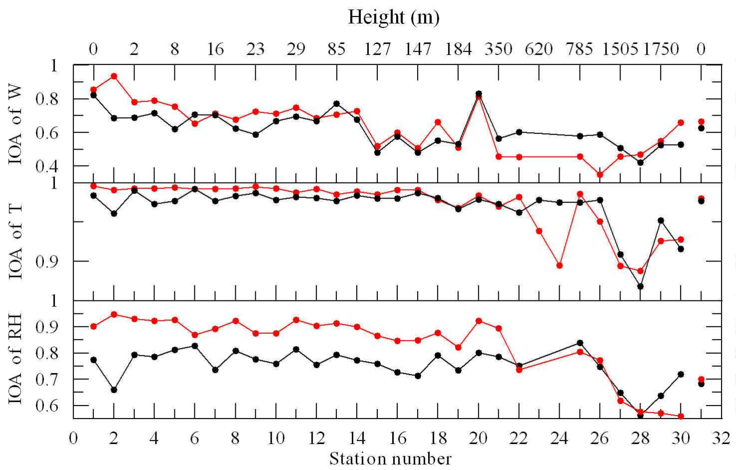

Figure 3. *IOA* values calculated for wind speed intensity (W), temperature (T) and relative humidity (RH). LAPS data in red and RAMS data in black.

Poor performances over mountain areas were expected from a diagnostic modelling approach based on a limited resolution input measurements network insufficient to resolve topographic features (Figure 1), as is shown by similar results reported in literature (e.g. Hiemstra *et al.*, 2006). The alpine valleys structure is anyway not resolved at the target model space resolution of 4 km. In order to evaluate model performances in topographic locations affected by highest pollutants concentrations, a deeper analysis has been performed for stations located over plains and rolling terrain (with terrain height lower than 300 m. a.s.l.).

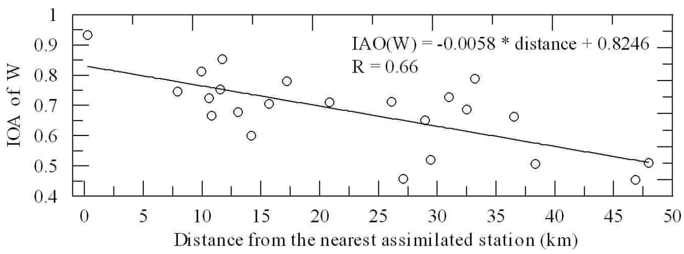

Figure 4. Laps *IOA* values decrease with increasing distance of the control stations from the nearest assimilated station; only stations with terrain height lower than 300 m. a.s.l. were selected.

Figure 4 highlights the expected increase of the LAPS model performances when the distance of control stations from the nearest assimilated decreases. This behaviour clearly represents the features of the adopted diagnostic approach providing best results when a sufficient number of good quality stations, representative of the surrounding territory, are assimilated. In

spite of the difficulties of building a comprehensive and verified database of meteorological observations at national level, our results show the potential success of this approach in improving mesoscale meteorological model performances.
The correction obtained by the meteorological analysis is exemplified by wind results described in Figure 5 for the stations of Udine and Grado. The overestimation of wind speed provided by RAMS, especially during the central part of the day, is removed by LAPS analysis producing a good reproduction of observations at the inland plain station of Udine and a moderate underestimation of measured data at the coastal lagoon station of Grado during the second half of the day. Even for the latter station LAPS anyway improves the reproduction of observed values (see e.g. station 3 in Figure 3 and Figure 6). The removal of wind intensity overestimation potentially causing underestimation of near surface pollutant concentrations is a valuable result for air quality applications.

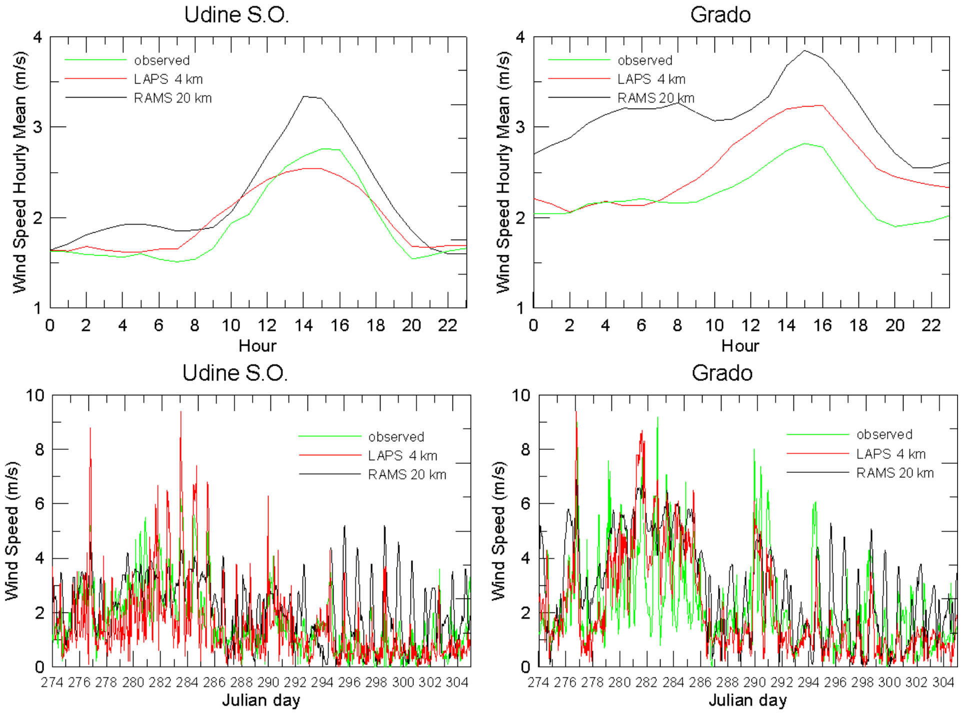

Figure 5. Comparison of wind speed simulated by RAMS (black line) and LAPS (red line) with measurements (green line) at Udine (inland plain station, left panel) and Grado (coastal station, right panel) for hourly average values (top panel) and values measured during October 2005 (bottom panel).

Figures 6 show respectively *IOA* and *FB* values for wind speed, temperature and humidity calculated for the 20 available stations located over the inland and coastal plain areas. In order to evaluate model performances with respect to diurnal cycle, four index values were calculated for each station, corresponding to four different hours of the day (0, 6, 12, 18 l.s.t.).

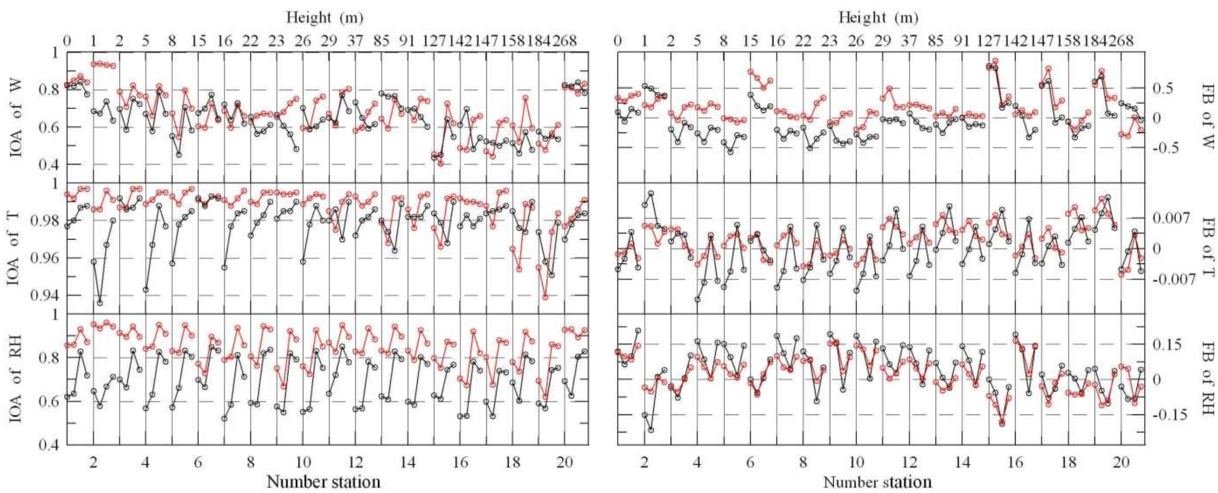

Figure 6. *IOA* (left) and *FB* (right) values calculated for coastal and inland plains stations. Four index values are presented for each stations corresponding to four different hours of the day (0, 6, 12, 18 Local Solar Time). Black line refers to RAMS and red line to LAPS.

Data assimilation clearly improves the reproduction of humidity values for all the stations for all the hours of the day: LAPS *IOA* values are always closer to 1 then RAMS ones (Figure 6, lower left panel). LAPS analysis correction is particularly effective for nocturnal humidity, that is generally underestimated by RAMS; diurnal overestimation, where present (see e.g. FB for stations 8 and 9 in Figure 6, lower right panel), is positively corrected too. The correction obtained for temperature is very effective for stations located at lower heights: LAPS *IOA* values are closer to 1 and *FB* closer to 0 than RAMS ones (Figure 6, middle panels). In particular, the temperature diurnal cycle is better reproduced: in most cases data assimilation corrects nocturnal overestimation and reduces diurnal underestimation. The presence of larger errors on nightly and early morning values is generally comprehensible due to the large influence on meteorological variables of local topographic conditions during nightly stable conditions and in absence of strong synoptic meteorological forcing.

LAPS analysis correction effect is less evident in *IOA* values for wind speed and shows more variation among stations, even if a general reduction of FB absolute values is detectable. In some locations LAPS performs better than RAMS, in some other no improvement can be noticed (Figure 6, upper panels). In general LAPS corrects RAMS wind speed overestimation leading to a slight underestimation at some locations. LAPS simulation produces only slight improvement with respect to RAMS results over hilly terrain.

It can be noticed that RAMS simulation of station number 15, 17 and 19 show relevant underestimation that is not improved by the LAPS analysis. These stations are located at the end of valleys strongly characterized by local winds that are very difficult to predict without assimilation of proper stations representative of local circulation.

CONCLUSIONS

The meteorological fields necessary to drive air quality simulations in the frame of MINNI project have been reconstructed by means of the diagnostic meteorological model LAPS, that has been used to downscale the background information provided by an annual simulation of the prognostic model RAMS. An evaluation of modelled meteorological fields has been carried out for year 2005 using Friuli Venezia Giulia Region meteorological monitoring network data set.

The comparison of RAMS and LAPS results with observations shows that:

- LAPS provides a generally better description of meteorological fields in the coastal and inland plain area, which is the main target for air quality assessment;
- it obtains better statistical indicators of model performance, for all the common meteorological variables.

The temperature diurnal cycle is better reproduced by LAPS and, in particular, it corrects RAMS nocturnal overestimation. A relevant improvement is obtained for humidity, that is important for air quality applications because humidity influences PM and OH formation. The correction imposed by LAPS over RAMS wind speed is less clearly interpretable from statistical indicators, even if FB indicates the correction of RAMS overestimation, that is changed into a slight underestimation in LAPS results. This feature is quite relevant due to the influence of wind intensity on pollutants transport and dispersion.

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